AN EXPERIMENTAL STUDY OF THE PERFORMANCE OF PCM-ENHANCED CELLULOSE INSULATION USED IN RESIDENTIAL BUILDING WALLS EXPOSED TO FULL WEATHER CONDITIONS

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ABSTRACT

Air conditioning energy consumption in summer represents a major concern in many areas with hot and humid climates. When incorporated into the walls of light-weight residential buildings, phase change materials (PCMs) can increase the effective thermal mass of the walls and shift part of the space cooling loads to off-peak hours. The thermal properties of pure phase change materials (PCMs) and those of the mixtures of PCMs with cellulose insulation were studied via differential scanning calorimeter (DSC) tests and mass change tests. To directly prove the concept that PCM-enhanced insulation can reduce the peak heat flux across walls as well as its potential to shift part of the space cooling loads to a later time of the day, the performance of PCM-enhanced cellulose insulation was studied using two small-scale testing houses exposed to full weather conditions during the summer seasons. The testing houses were air-conditioned and independently metered. Both houses had identical thermal responses prior to any retrofits. Before the tests, the PCM enhanced insulation was blown into the wall cavities in one test house while plain cellulose insulation was installed in the other house for comparison purposes. Hourly heat fluxes and daily heat flow data for four walls are presented. Based on the results, important recommendations are provided for the optimal use of PCMs in insulation systems.

INTRODUCTION

In most regions of the United States, air conditioning electricity usage tops the list of energy consumption in buildings during the summer. In fact, household air conditioning represents about 16% of the annual total electricity consumption in the U.S. (EIA, 2001). The space cooling loads for light framed wood construction residential buildings and for some commercial buildings reach their peaks at about the same time of the day, usually in mid to late afternoon. Because the electricity consumption of air conditioning increases with space cooling load, a large electricity demand peak is created, which creates the following concerns: 1) More new electricity generation facilities are needed; 2) more generation energy is used to meet the electricity peak demand; and 3) extra demand is placed on the electricity transmission and distribution systems.

In addition to the construction of more electricity generation facilities on the “supply side”, there are several ways to approach this peak demand problem with “demand-side” management, among which shifting part of the peak load to off-peak time is a promising one. Sensible heat storage materials, like concrete and stone, are too heavy for residential building structures for this purpose. Phase change materials (PCMs), on the other hand, can absorb large amounts of latent heat when melting. This heat is released in the PCMs’ solidification process when the wall of the building cools down in the evenings, night, and/or early mornings. When placed in the wall of residential buildings, PCMs absorb part of the heat transferred from outside during the daytime, and release the absorbed heat when the environment cools down. In this way, PCMs can shift part of the cooling load from daytime to nighttime, when less cooling is needed, and lower the peak space cooling load. Or, depending on outdoor temperature swings, PCMs may eliminate some of the cooling load on any given day.

Cellulose insulation is made of recycled newspaper. Fire retardant is added to provide high fire safety rating. Its installation into walls and attics is relatively easy. Because the insulation fibers absorb, and/or trap liquid PCMs, no other containment method is needed to hold the PCM within the insulation. The mixture can be blown into the wall cavity without any change to the blowing machine. From observation of PCM-insulation mixture after several months’ test, it was found that there was no settling down problem. And very few stains of PCM were observed on the wall board. In addition, the PCM mixing process can be easily incorporated into the manufacturing process of the insulation. All these make PCM-mixed cellulose insulation a more convenient and practical way to incorporate the PCM in building walls than other proposed methods like Macro and Micro-encapsulation and direct impregnation with building materials (Zhang, 2005; Schossig, 2005; Feldman, 1991).

In this paper, the thermal properties of pure phase change materials (PCMs) and those of mixtures of PCMs with cellulose insulation were studied via differential scanning calorimeter (DSC) tests and mass change tests. Field tests were also conducted using two identical test houses. Heat fluxes and daily heat flow data for four walls (N, S, E, W) were collected and analyzed. The results are presented in this paper. Based on the results, important recommendations are provided for the optimal use of PCMs in insulation systems.

STUDY OF THE PROPERTIES OF PCMS

Phase Change Materials (PCMs) can be generally divided into three categories: organic, inorganic and mixtures, as shown in Figure 1. Among them, paraffin and hydrated salt are the two most commonly proposed PCMs for building applications.

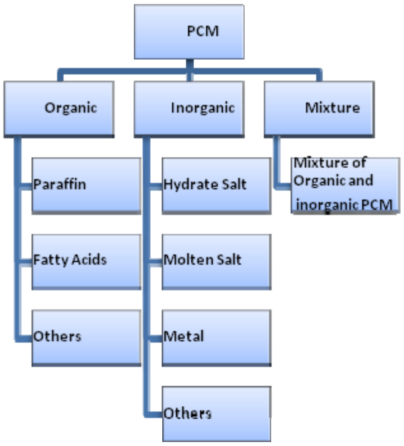

Figure 1. Types of PCMs

Paraffin

Paraffin is a straight-chain or branched saturated organic compound with the composition C_nH_{2n+2} (Freund, 1982). It is nontoxic, noncorrosive, and stable white crystal substance. When mixed with cellulose insulation, melted paraffin scatters and is absorbed by the insulation fibers. DSC tests were performed to investigate property changes of paraffin-based PCM-enhanced cellulose insulation, with a mass ratio of paraffin to cellulose of 0.7 to 1. A comparison between pure paraffin and a cellulose-paraffin mixture are shown in Figures 2 and 3. When mixed with cellulose, the DSC melting curve did not change significantly from that of the pure paraffin, but the solidification curve was broadened. The solidification point also did not change significantly, but the latent heat of fusion of the mixture decreased when compared to that of pure paraffin. If it were assumed that the cellulose did not change the properties of the paraffin, the latent heat of fusion should be 56.83 J/g. The test results, however, yielded 60.45 J/g. Therefore, one observation is that the cellulose would broaden the width of the solidification peak but would not significantly affect the latent heat of fusion and melting process. This means that the paraffin could still store heat after being mixed with cellulose insulation.

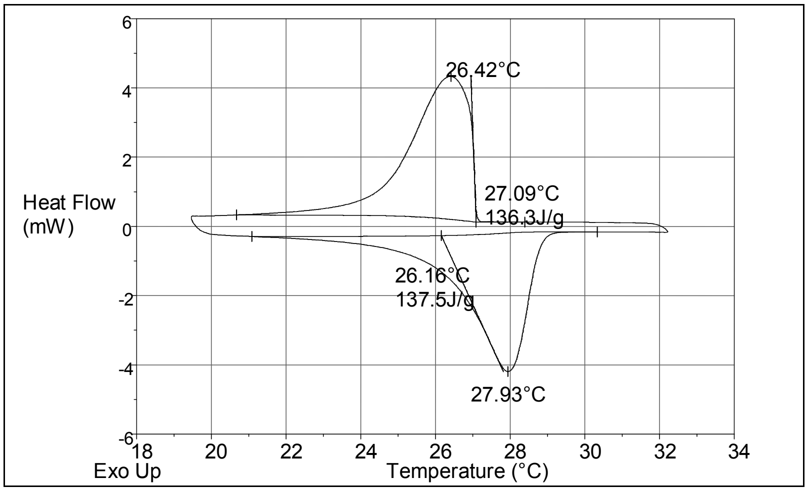

Figure 2. Melting Curve of Pure Paraffin

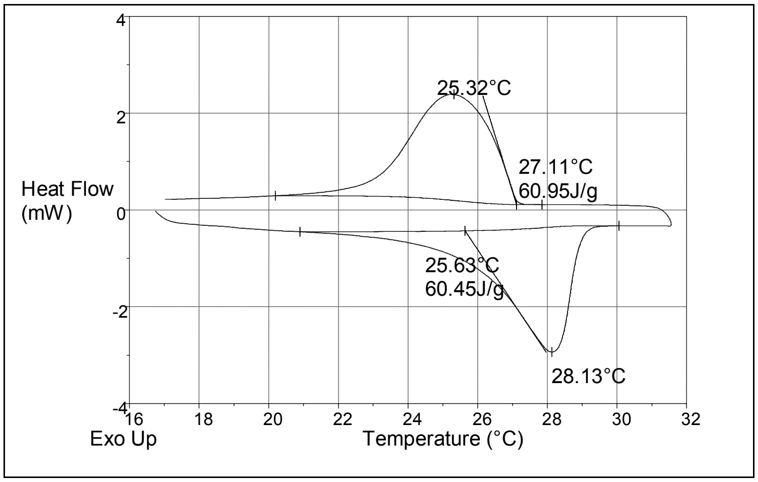

Figure 3. Melting Curve of Paraffin-Cellulose Mixture

An important issue for the integration of PCM in cellulose insulation was how much paraffin could the cellulose hold. After mixed with paraffin, the cellulose insulation looked darker. When a large amount of paraffin was added, there were clusters of paraffin found at the bottom of the insulation. From observation, about 200% of the weight of the insulation was the limit of paraffin the insulation could hold. Above this concentration, the clusters of paraffin became troublesome. Though, at lower concentration(30% by weight of the insulation), the conductivity of the mixture doesn't change much (Kośny, 2003), when the concentration gets above 200%, the insulation was not as loose as the plain insulation, which in turn might lower the R-value of the insulation by minimize the portion of the air in the insulation and could potentially cause installation problems.

Hydrated Salt

Hydrated salts are formed by anhydrous salts and a few fixed number of water molecules, which are usually called "water of crystallization" (Telkes, 1980). Hydrated salts have relatively high conductivity, density and large latent heat of fusion. All the hydrated salt-based PCMs are hygroscopic (i.e., when not placed in a sealed container, they will absorb moisture from air and change properties). To prove this point, hydrated salt PCMs were placed in small metal containers with holes punched on the lid. These containers were weighted over time. Mass change results are shown in Figure 4. The weight of the samples increased by about 50-60% in less than 10 days, after which the mass remained constant.

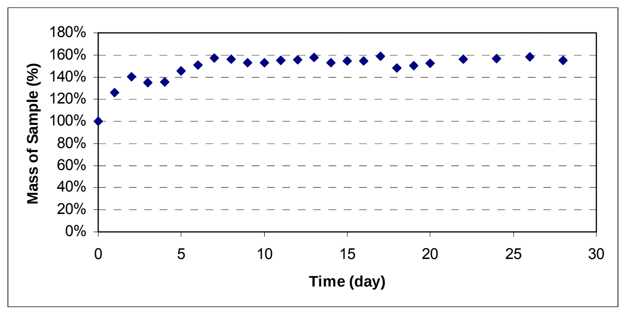

Figure 4. Mass Change of Hydrated Salt Over Time

DSC tests were performed on both new unexposed hydrated salt samples and 'wet' samples. The results are shown in Figures 5 and 6. By comparing the new and 'wet' samples, it was found that hydrated salts lost most of their heat storage capacity after absorbing moisture. In fact, for the 'wet' samples, only a small valley remained from the original phase change temperature range during melting. That is, their latent heat of fusion dropped from 131.4 J/g to 1.2 J/g. Thus, without some proper coating or encapsulation, hydrated salt PCMs can not be used in building applications by simply mixing them with the insulation.

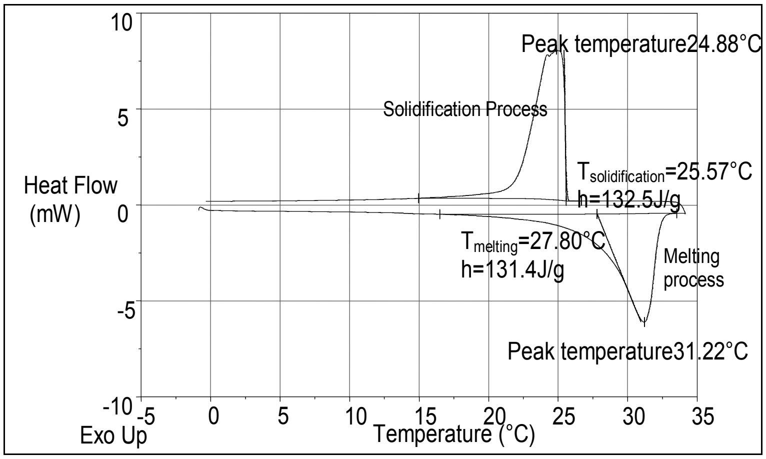

Figure 5. DSC Curve of New ('Dry') Hydrated Salt

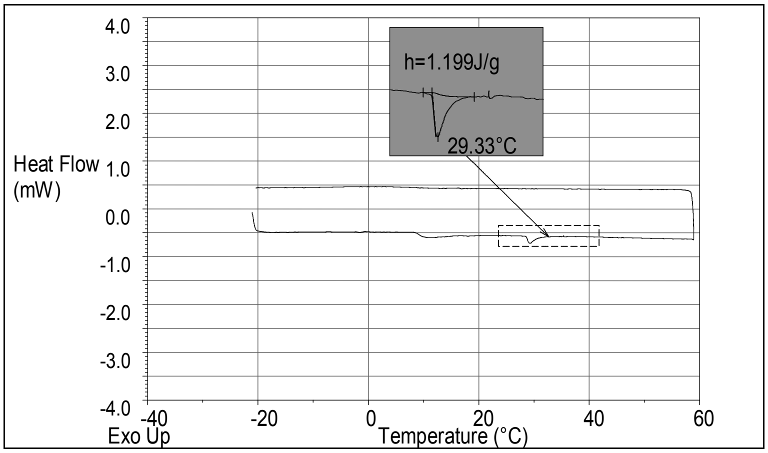

Figure 6. DSC Curve of 'Wet' Hydrated Salt

FIELD TESTING

In the effort to prove the idea of using PCM-enhanced insulation for peak heat transfer rate reduction and for shifting the space cooling loads, field tests were performed. Paraffin was melted and evenly mixed with cellulose insulation by spraying and agitation. For easy comparison with previous research (Zhang, 2005; Zhu D., 2005), the concentration of paraffin used was defined on the basis of the weight of paraffin by the weight of the gypsum board. For the 0.1-m (4-in) frame walls, 30% by weight of the gypsum board was equivalent to a paraffin weight of about 72% of the weight of the cellulose insulation in the wall cavity. The field tests were conducted during June and July, the two hottest months of a year under the local climate.

The field tests were performed using two identical small-scale testing houses located in Lawrence, Kansas, USA. The test houses were about 1.83 m by 1.83 m by 1.52m (6 ft by 6 ft by 5 ft high) and were constructed using typical residential house frame wall structures. The two test houses and their space cooling system are shown in Figure 7. A chiller produced chilled water at 7.2^{o}C (45^{o}F), which provided space conditionings via fan coil units.

Figure 7. Test houses and cooling system

Type "T" thermocouples were installed to measure the exterior wall surface temperatures, indoor wall surface temperatures and indoor air temperatures. Nine thermocouples were installed on each wall and all the thermocouples were shielded to minimize radiation effects. Four heat flow meters were installed on each interior wall to monitor the heat flow through the walls. In later analysis, the test data were averaged for each wall. A data logger and a computer collected the data at intervals of 10 seconds.

Before the test, a calibration test was performed to eliminate any possible errors from the test system. In the calibration test, both test houses were installed with plain cellulose insulation. The performance of two houses (heat flow through the wall and surface temperature) was very close to each other. The west wall heat flux is shown in Figure 8. The outside and inside west wall surface temperature for the last three days is shown in Figure 9. The small relative difference in thermal performance of the walls would qualify later differences as those produced solely by the addition of PCM to the cellulose insulation.

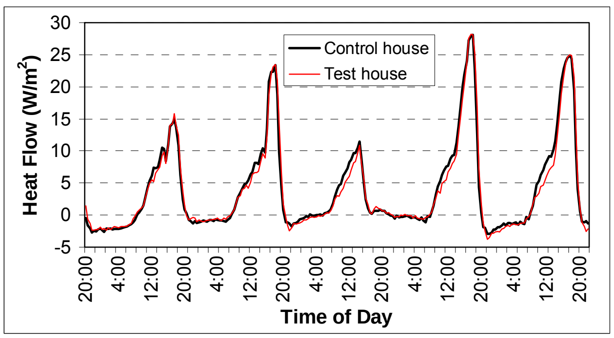

Figure 8. Heat Fluxes of the West Walls (Calibration Test)

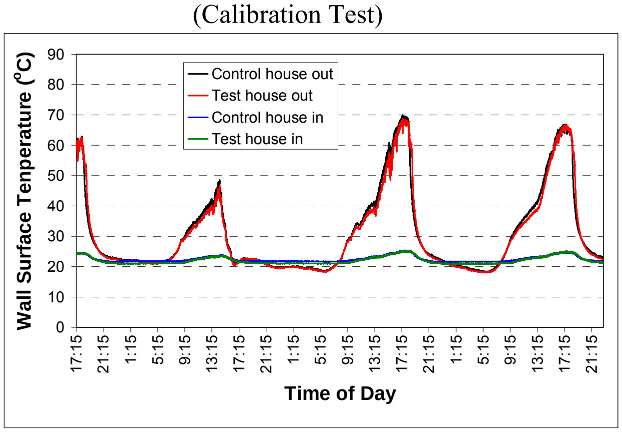

Figure 9. Outdoor and indoor west wall surface temperature (Calibration Test)

RESULTS AND ANALYSIS

The continuously collected (every 10 seconds) heat flux data were averaged for every half hour, which minimized the effects caused by sudden changes in wind speed, passing clouds, and/or indoor temperature fluctuations produced by the cooling system's "on/off" cycles. The half-hourly averaged heat fluxes through the four walls for several typical hot days are shown in Figures 10 – 13. The outdoor air temperatures are shown in Figure 14.

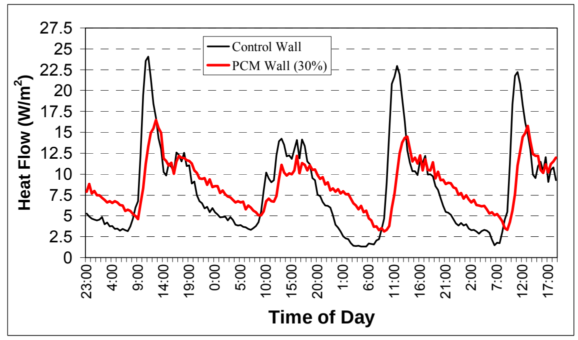

Figure 10. Half-Hourly Averaged Heat Flux of East Wall (30% PCM)

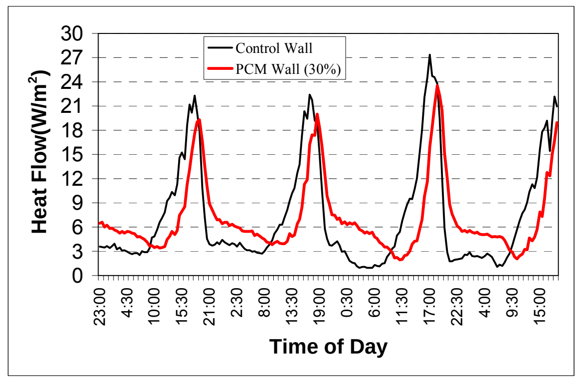

Figure 11. Half-Hourly Averaged Heat Flux of West Wall (30% PCM)

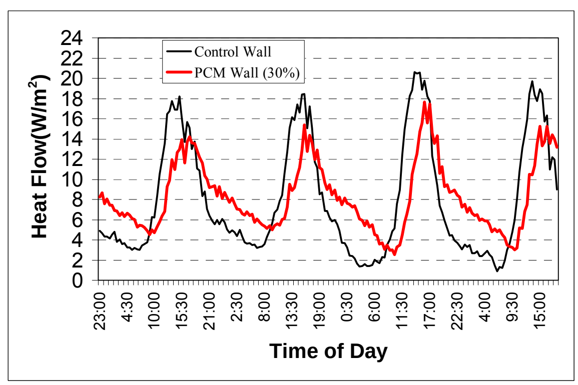

Figure 12. Half-Hourly Averaged Heat Flow of South Wall (30% PCM)

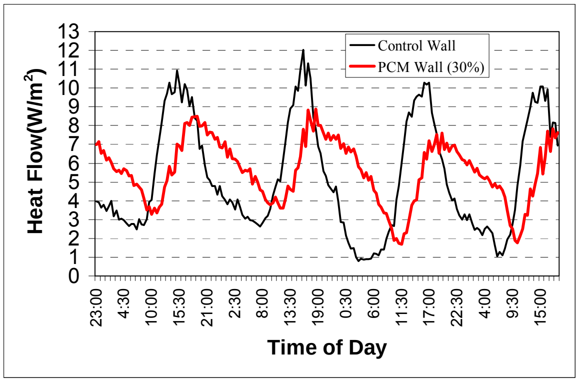

Figure 13. Half-Hourly Averaged Heat Flux of North Wall (30% PCM)

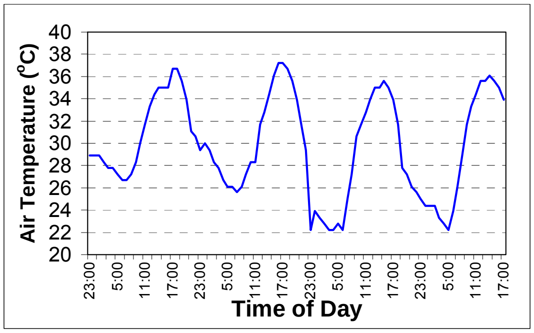

Figure 14. Outdoor Air Temperature

The test results showed that, for all four walls (i.e., E, W, S, N), the peaks of heat transfer rate of the PCM walls were delayed a couple hours when compared to those of the control walls. On average of data from the days in the figures, the peak hour shift for the east wall was 1.8 hour; for the west wall, it was 1.3 hour; for the south wall it was 1.4 hour; for the north wall it was 3 hour.

The absolute peak values for the PCM walls decreased. The east wall and north wall had larger peak reductions while the west wall and south wall's reductions were relatively small. The heat flux values of the PCM walls during the heating up periods (before the peaks) were lower than those of the control walls because the PCMs were melting. The heat flux values during the cooling down period (after the peaks) were higher in PCM walls than those of the control walls because of the PCM solidification process. Part of the space cooling load was successfully shifted to off-peak times. Thus, the concept of using PCM to shift the space cooling load was proven.

In addition, it was found that for each wall, the areas under the control wall and PCM curves, which represented the total heat flow into the house through the wall in a day, were about the same. Therefore, PCMs could reduce the peak heat flux value but, on the daily basis, PCM-enhanced insulation would not save energy because the saving by the melting process in the daytime would be balanced by solidification process at nighttime.

From the study of all the test data, it was found that, under different weather condition, the peak reductions varied. Relatively cool days with low peak heat flux values for the control wall, though not always, tended to have larger reduction. For example and on average, for the east wall the peak reduction was 38.2%; for the west wall it was 23.3%; for the south wall it was 19.5%; and for north the wall it was 27.9%.

Other than the peak reductions, under different weather condition, the peak hour shifted by the PCM also varied. On average, the peak hour shift for the east wall was 1.7 hour; for the west wall, it was 1.4 hour; for the south wall it was 1.9 hour; for the north wall it was 3.1 hour.

Another finding was that not only did the peak value but also the shape of the heat flux curve affected the performance of the PCM-enhanced insulation. Take the heat flux curve for the one day shown in Figure 15 for instance. The peak heat flux value of the control wall was high. The percent peak reduction was large. In contrast, although the peak heat flux shown in the day of Figure 15 was of the same value as that of the day of Figure 15, the percent reduction was lower for this day than for the day shown in Figure 15. That is, as depicted in Figure 15, the heat flux curve of the control wall was narrow and steep. As shown in Figure 15 and 16, "narrow" shape day's outdoor air temperature remained cool for the first part of the day and rose rapidly in latter part of the day. On average, the temperature in the 'Narrow' Shape day was lower than the temperature of the day with "wide" shaped peak, though the maximum values are close to each other. For the days with cooler outside environment, the PCM melts slowly before the peak hour, which helps in decreasing the peak value.

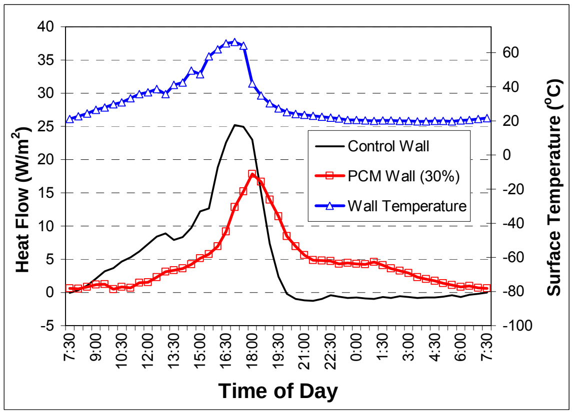

Figure 15. Heat Flux for a 'Narrow' Shape Day

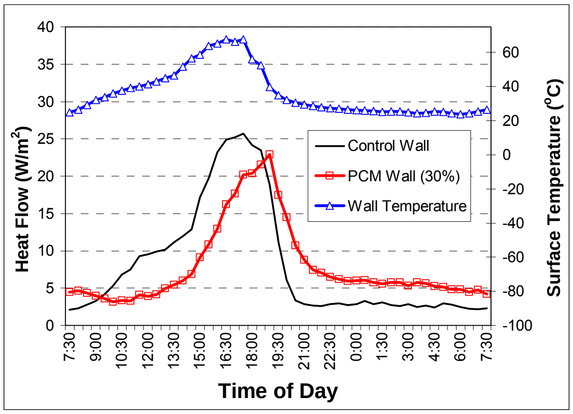

Figure 16. Heat Flux for a 'Wide' Shape Day

SUGGESTIONS FOR THE VARIOUS WALLS

If the radiation heat transfer between the surfaces in the room were neglected, the sum of the heat flow of four walls would be the total space cooling load across the walls. Because the shapes and orientations of US residential buildings vary, it is difficult to decide the relative importance of each of the walls in the sum. In this paper, the house was assumed to be a cubic box (i.e., the relative importance – statistical weights -- for the four walls were the same).

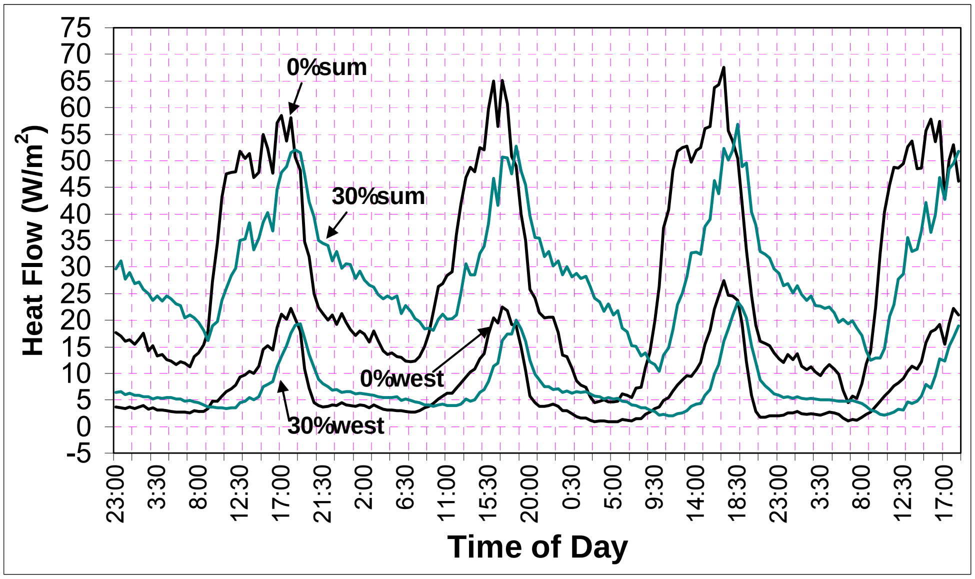

Figure17. West Wall Heat Flux and the Sum of All Four PCM Walls

West Wall

From Figures 10 – 13, it was found that the west wall's heat flux values were significantly higher than the other three walls in the late afternoon. It was the dominant force in the heat flow sum of four walls. As shown in Figure 17, it was the west wall that commanded the peak hour of the sum for both 30% PCM-enhanced insulation test house and the 0% control house. Also, because its peak hour was always the latest, the peak reduction in the west wall was always helpful. Therefore, to get larger cooling load peak reduction, the west wall's peak should be reduced as low as possible.

North Wall

Because there is no direct radiation on the north wall, the heat flow value of the north wall is always low. North wall's influence on the sum peak value is minor. From an economic point of view, the payback of the PCM in north wall is low. Thus, except for the buildings with large north walls, it is not necessary to install PCM north walls.

East Wall

In order to lower the peak cooling load, the peak hour of the wall should be behind or, at least, close to the peak hour of cooling load. Otherwise the PCM in the wall will only increase the peak value of cooling load (the four walls' sum, if other loads are not considered). The east wall's peak is in the morning. In the later afternoon, when the cooling load reaches its peak, the heat flow value of the east PCM wall is higher than those of the control walls as a result of the PCM solidification process.

Because east wall's peak is in the morning, in order to shift its peak to late afternoon, either very high concentration or some PCM with very high latent heat of fusion would be needed, which may beyond the holding limit of the cellulose insulation. In addition, although the heat flow peak of the east wall is high, as shown in Figure 18, its heat flow in the afternoon was close to that of the north wall. That was the case because, similar to the north wall, there is no direct radiation on the east wall. For the same reason as the north wall, it would not be economical to add PCM in east walls.

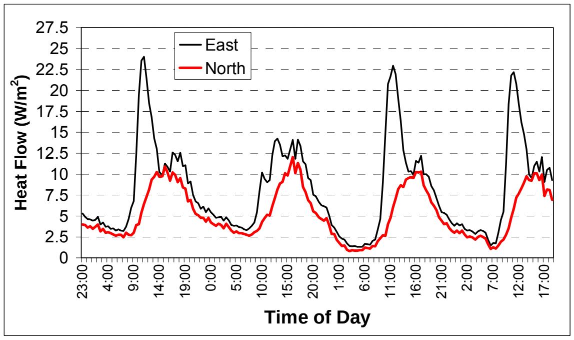

Figure 18. Comparison of Heat Flux Between East Wall and North Wall

<u>South Wall</u>

South wall's peak heat flux hour was in between the peak hours of the east and north walls. Its peak value in the afternoon was always higher than those of the east and north walls. If the same concentration and type of PCM-enhanced insulation was used for all the walls it was found that the peak hour of the south wall was always ahead of the peak hour of the sum of the four walls. Thus, the south wall faced the same problem as the east wall, as discussed above: PCM in the south wall increased the peak value of the room cooling load. Therefore, except for when other cooling loads (for example, internal loads) are large enough to make the total cooling load peak lead the south wall peak and/or if the south wall is large (dimension wise), there is no need to install PCM in south wall.

CONCLUSIONS

1. From sample mass tests and DSC tests, it was found that the hydrated salts would absorb water in amounts of about 50-60% of their weight and lose their thermal storage capacity, when exposed to air. Therefore, hydrated salts should not be used in insulation unless encapsulated.

2. Mixing paraffin with insulation won't change the paraffin's properties significantly. Thus, paraffin-based PCMs could be used to enhance cellulose insulation.

Field tests were carried out under full weather conditions. Calibration tests showed that both testing houses had identical thermal responses. A cellulose-PCM mixture (30% PCM by weight of the inside wallboard) was installed in four walls in the test (retrofit) house. Test results showed that the PCM-enhanced insulation can shift the peak cooling load and can lower the peak heat transfer rate. On average, the peak heat flux values were reduced as follows: for the east wall, the reduction was 38.2%; for the west wall, it was 23.3%; for the south wall, it was 19.5%; for the north wall, it was 27.9%. The peak hour shift for the east wall was 1.7 hour; for the west wall, it was 1.4 hour; for the south wall it was 1.9 hour; for the north wall it was 3.1 hour. Relative cool days tended to have larger reductions.

3. From the test results, it was found that PCM-enhanced insulation could only reduce the peak value; on a daily basis, PCM would not save energy because the saving by the melting process in the daytime would be balanced by solidification process at night.

4. The west wall was recommend to undergo the proposed cellulose-PCM retrofit and the attempt should be made to reduce the heat transfer rate be as much as possible, whether by using a PCM with a high latent heat, or by increasing the quantity of the PCM to an optimal value. There is no need to install insulation in east walls. Whether the south and north walls should undergo the proposed retrofit would depend on different factors, such as building internal loads and wall areas.

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